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13. ABSTRACT (Maximum 200 words)  This three-year grant is now completed, although an augmentation grant is still continuing the work along new lines. In this grant, we developed the analysis and simulation tools necessary to treat rotorcraft design problems when the rotorcraft has unsteady or unknown RPM. The tools developed include a Fast Floquet theory that can be applied to rotorcraft with multiple rotors and unknown RPM, a new spatially-based Fourier Series Method, several types of auto-pilots and discrete auto-pilots, and hybrid combinations of methods. The work also developed a mathematical theory of trim that includes unsteady and unknown RPM in the development as well as numerical and experimental test beds on which to test new methods.  <b>DTIC QUALITY INSPECTED 2</b>				
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**Multidisciplinary Rotorcraft Analysis  
and Simulation**

David A. Peters

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U. S. Army Research Office

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# FINAL TECHNICAL REPORT

ARO Grant No. DAAH04-94-G-0351

Multidisciplinary Rotorcraft Analysis and Simulation

1 September 1994 through 31 August 1997

by

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## Objectives

The objective of this research is to develop solution methodologies for rotorcraft analysis and simulation that will be applicable to multi-disciplinary modeling (including dynamics, aerodynamics, control, and engine/drive-train dynamics). The strategies developed are to be applicable to systems for which the period of motion is unknown or for which there are several rotors with differing periods.

## Approach

The approach taken is as follows:

1. Assemble a representative set of rotorcraft equations that includes rotor dynamics, blade lift, dynamic wake, engine-drive-train, engine control, stability augmentation, fuselage, and auto-pilot.

The purpose of this work is not to develop new models for these components nor is it to assemble the state-of-the art models for each piece. Rather, it is to use the simplest model of each component that will allow realistic interaction among components.

2. Study the assembly and solution of these equations in hover for non-constant RPM to determine what pieces of conventional wisdom fail.
3. Modify existing trim methodologies such that they can be applied to general systems with variable RPM and multiple rotors.

4. Apply and test the modified methods on problems of forward-flight trim and stability

### Accomplishments

In this project, we have completed all of the goals and objectives of the original proposal. We have produced 17 publications, and graduated two Doctoral Students and two Master's Students. In addition, we have developed some new approaches, not envisioned in the original proposal, which have resulted in AASERT funding for two additional graduate students.

Perhaps the most crucial aspect of our research was development of a Mathematical Theory of Trim. This work is reported in References 3 and 4. This is not a method of trim, but is a theoretical framework by which any trim methodology can be evaluated. Theorems, which are part of the development, show when a particular system is "trimmable" or "solvable" and show why certain trim techniques will fail when a system has poles at the origin. The theory of trim offered insight and suggestions as to new trim methodologies which we have proposed. It also expanded the concept of trim into the area of "optimal trim".

A second important aspect of our work was the study of finite elements in time as a trim methodology. References 7 and 14 describe this work. The theory of trim showed that finite elements in time were just a special case of constrained Ritz-Galerkin methods that also includes Fourier series and the Sinha approach, Ref. 4. Our own work showed how space and time could be unified in such methods. It also showed (numerically and theoretically) why the Sinha approach was so inefficient.

A third area of development was the development of Fast Floquet Theory and Fast Trim methodologies. These developed out of (and helped formulate) the mathematical theory of trim, Refs. 1, 3, 5, 9, and 15. They make use of the rotor planes of symmetry to reformulate the trim problem. This area was not originally foreseen in the proposal.

A fourth accomplishment is in the area of auto-pilots, Refs. 6, 10, and 17. Once we could see from the Theory of Trim what the defects of auto-pilots were, we could design new and better versions. Ultimately, this led us to the class of discrete auto-pilots, a thrust not envisioned in the original proposal, Refs. 8, 12, and 13. This work still continues with the study of discrete controllers, discrete observers, and construction of an experimental test bed. These methods further evolved into the "non-updated Jacobian" method of periodic shooting for trim.

The fifth area of our research was in the area of Fourier Series solutions. As with the other methods, our Theory of Trim showed that poles at the origin (along with unknown RPM) created

a fundamental change in Fourier analysis. This led us to the development of quasi-periodic analysis and more general series, Refs. 11, and 16. Most interesting was the development of a spatial Fourier Series (rather than time) which removes the unknown period from the equation for problems with unsteady or unknown RPM.

Finally, an important element of this work was the development of numerical test beds for verification of the theory and methods. One of the main test beds was a rotorcraft model that included a 6-DOF rigid fuselage, two rotors with flap-lag degrees of freedom and dynamic inflow, and engine dynamics. This model was used to test out the theories of trim including "optimum trim" with over 90 states. Reduced versions of this model included a flap-lag model of a single rotor with engine dynamics, used by Jorge Morillo, and flap-lag rotor dynamics with a 2-DOF fuselage used by Si-Hao Li. These test beds allowed realistic simulations of test cases.

### Interactions

Our group had strong interactions with several other groups around the country. We made two trips to Florida Atlantic University to share our results. Professor Gopal Gaonkar and his group at Florida Atlantic University are now using our Fast Floquet, Fast Trim, and Periodic Shooting. We have also had strong interactions with Georgia Tech and with their Rotorcraft Center. Professor Olivier Bauchau there has used our Fast Floquet Theory. We also have interacted with Professor Friedmann of the University of California, Los Angeles, whose students are now using one of our auto-pilots to trim.

### Publications

#### Journals

1. Peters, David A., "Fast Floquet Theory and Trim for Multi-Bladed Rotorcraft," *Journal of the American Helicopter Society*, Vol. 39, No. 4, October 1994.
2. Peters, David A., "Some Observations on the Sinha Approach to Dynamic Response Calculations," *Journal of Sound and Vibration*, Vol. 188, No. 4, December 1995.
3. Peters, David A., and Barwey, Dinesh, "A General Theory of Rotorcraft Trim," *Mathematical Problems in Engineering*, Vol. 2, No. 1, January 1996.

## Proceedings

4. Peters, David A., and Barwey, Dinesh, "A General Theory of Rotorcraft Trim," 36th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, New Orleans, April 10-12, 1995, Paper No. 95-1451.
5. Peters, David A., "Fast Floquet Theory and Trim for Multi-Bladed Rotorcraft," Proceedings of the 51st Annual National Forum of the American Helicopter Society, Ft. Worth, May 9-11, 1995.
6. Peters, David A., and Li, Si-Hao, "A Combined Periodic-Shooting, Auto-Pilot Technique for Rotorcraft Analysis," *Computational Mechanics '95*, Proceedings of the International Conference on Computational Engineering Science, Mauna Lani, Hawaii, July 30-August 3, 1995, pp. 654-659.
7. Zhao, Bo and Peters, David, "Space-Time hp-Finite Elements with Moving Loads and Moving Constraints," ASME 15th Biennial Conference on Vibration and Noise, Boston, September 17-21, 1995.
8. Schmitt, John M., Bayly, Philip V., and Peters, David A., "Stabilization of Periodic Flap-Lag Dynamics in Rotor Blades," ASME 15th Biennial Conference on Vibration and Noise, Boston, September 17-21, 1995; and AHS 2nd International Aeromechanics Specialists' Conference, Bridgeport, CT, October 11-13, 1995.
9. Peters, David A., and Beaver, Rochelle D., "Application of Fast Floquet Theory to Rotor Flap Response with Dynamic Inflow," AIAA Dynamics Specialists' Conference, Salt Lake City, April 18-19, 1996, Paper No. 96-1216.
10. Peters, David A., Bayly, Philip, and Li, Sihao, "A Hybrid Periodic-Shooting, Auto-Pilot Method for Rotorcraft Trim Analysis," Proceedings of the 52nd Annual National Forum of the American Helicopter Society, Washington, DC, June 4-6, 1996, pp. 780-794.
11. Peters, David A., and Morillo, Jorge, "Harmonic Balance Approach for Rotorcraft with both Unsteady and Unknown Rotor Speed," Proceedings of the 38th AIAA Structures, Structural Dynamics, and Materials Conference, Kissimmee, Florida, April 7-10, 1997, Paper No. 97-1095.

12. Schmitt, John, Bayly, Philip, and Peters, David, "Stabilization of Periodic Flap-Lag Dynamics in Rotorcraft," presented at the IUTAM Symposium on New Applications of Non-linear and Chaotic Dynamics in Mechanics, Cornell University, July 27-August 1, 1997.
13. Bayly, Philip, Schmitt, John, and Peters, David, "Stabilization of Period-Coefficient Flap-Lag Dynamics through Application of Discrete Control," Seventh International Workshop on Dynamics and Aeroelastic Stability Modeling, St. Louis, October 14-16, 1997.

### Theses

14. Zhao, Bo, *Space-Time hp-Finite Elements and Post-Processes Stress and Momentum*, Doctor of Science Thesis, Washington University, May 1995.
15. Beaver, Rochelle D., *Applications of Fast Theory to Rotor Flap Response with Dynamic Inflow*, Master of Science Thesis, Washington University, December 1995.
16. Morillo, Jorge A., *A New Harmonic Balance Approach for Rotor Systems with Engine Dynamics*, Master of Science Thesis, Washington University, December 1996.
17. Li, Sihao, *A Hybrid Periodic-Shooting, Auto-Pilot Method for Rotorcraft Trim Analysis*, Doctor of Science Thesis, Washington University, May 1997.

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